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# Thermoregulatory responses to intermittent exercise are influenced by knit structure of underwear*

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**Summary.** The purpose of this study was to evaluate the role of knit structure in underwear on thermoregulatory responses. Underwear manufactured from 100% polypropylene fibres in five different knit structures (1-by-1 rib, fleece, fishnet, interlock, double-layer rib) was evaluated. All five underwear prototypes were tested as part of a prototype clothing system. Measured on a thermal manikin these clothing systems had total thermal resistances of 0.243, 0.268, 0.256, 0.248 and 0.250 $m^2 \cdot K \cdot W^{-1}$, respectively (including a value for the thermal resistance of the ambient environment of 0.104 $m^2 \cdot K \cdot W^{-1}$). Human testing was done on eight male subjects and took place at ambient temperature ($T_a$) = 5° C, dew point temperature ($T_{dp}$) = −3.5° C and air velocity ($V_a$) = 0.32 $m \cdot s^{-1}$. The test comprised a repeated bout of 40-min cycle exercise (315 $W \cdot m^{-2}$; 52%, SD 4.9% maximal oxygen uptake) followed by 20 min of rest (62 $W \cdot m^{-2}$). The oxygen uptake, heart rate, oesophageal temperature, skin temperature, $T_a$, $T_{dp}$ at the skin and in the ambient air, onset of sweating, evaporation rate, non-evaporated sweat accumulated in the clothing and total evaporative loss of mass were measured. Skin wettedness was calculated. The differences in knit structure of the underwear in the clothing systems resulted in significant differences in mean skin temperature, local and average skin wettedness, non-evaporated and evaporated sweat during the course of the intermittent exercise test. No differences were observed over this period in the core temperature measurements.

**Key words:** Thermoregulatory responses — Cold — Intermittent exercise — Underwear

## Introduction

Thermoregulatory responses of the nude man resting and exercising in various thermal environments have been well documented (Saltin and Hermansen 1966; Stolwijk et al. 1968; Nielsen 1969). This is not the case for the clothed man. The clothing acts as a dynamic thermal enclosure around the human body creating a thermal microenvironment. Clothing buffers the heat exchange of man with the surrounding climate; however, it may also limit the possibilities for heat dissipation. Mean skin temperature ($\bar{T}_{sk}$), skin temperature ($T_{sk}$) distribution, evaporation of sweat and skin wettedness (w) are some of the responses that may change with different clothing parameters. The heat exchange between the skin surface under the clothing and the ambient environment through the clothing worn on moving man cannot be explained only in terms of standard textile characteristics. In addition to the heat exchange across the textile layers, passive and forced convective air movements in the clothing and through the openings of the garment remove a varying amount of heat energy depending on garment design, and also on body movements, air velocity, wetting, compression and other factors (Hall and Poltke 1956; Nielsen et al. 1985). Also, changes in ambient air humidity or sweating will change the humidity within the clothing which may produce wetting of the clothing. As a result, transient heat

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exchange develops within the clothing. This affects the heat exchange between the skin surface and the micro-environment, and provides a feedback to the thermoregulatory responses at the skin surface.

Common clothing ensembles used in cold environments are comprised of two or more clothing layers: underwear, possibly middle layers, and an outer clothing layer. The majority of the skin surface is not in contact with the ambient environment, but with the micro-environment under the clothing and the underwear itself. Thus, underwear has a special function in relation to the sensation of the fabric-to-skin interface and may also be of importance for the resulting micro-environment over the skin.

In the literature (Fonseca 1970), the addition of thermal underwear to a clothing system is supposed to add little extra warmth and protection for the wearer, and in terms of differences in intrinsic thermal resistance of the underwear measured on a thermal manikin these differences are insignificant, as long as the fit and design remain the same (Olesen and Nielsen 1983). However, it has been shown on humans that the textile material in the underwear of a clothing system slightly influenced the thermoregulatory responses during intermittent exercise in a cold environment (Holmér 1985).

The purpose of the present study was to investigate if underwear manufactured from material of the same fibre type, but in different knit structures, as a part of a clothing ensemble, would cause different thermoregulatory responses in people performing intermittent exercise in an environment which provoked periods of both sweating and chilling.

## Methods

*Garment description.* Underwear manufactured from 100% polypropylene fibres in five different knit structures [1-by-1 rib (K1), fleece (K2), fishnet (K3), interlock (K4), double-layer rib (K5)] were evaluated. Measurements of selected physical characteristics of the experimental textiles were performed on single and multi-layer samples of cloth in accordance with standard procedures: fabric thickness in mm (ASTM: D1774-64), thermal resistance in $m^2 \cdot K \cdot W^{-1}$ (ASTM: D1518-77) and water vapor resistance in $m^2 \cdot Pa \cdot W^{-1}$ (DIN: 54101). The results are shown in Table 1. Before any testing was done, all samples were laundered and air-dried five times without the use of any detergent. This was done to remove excess finishing chemicals in the textiles. All five underwear prototypes were tested as part of a typical, standardized clothing system on human subjects. The clothing system was comprised of a two-piece long-sleeved, long-legged, underwear ensemble, a battle dress uniform (BDU) shirt and trousers (50% cotton, 50% nylon), woollen socks, gym shoes, and woollen gloves. Each subject had his own separate clothing system. Before any testing was done on humans, all underwear and the rest of the clothing system were laundered as described above. For each subject the experimental underwear was tested in randomized order. Insulation values of all five clothing systems and all five underwear ensembles were measured on a thermal manikin (Madsen 1971).

**Table 1.** Physical characteristics of the textiles applied and of the garments measured on a thermal manikin

| Knit structure | 1-by-1 rib K1 | Fleece K2 | Fishnet K3 | Interlock K4 | 2-layer K5 | BDU |
|---|---|---|---|---|---|---|
| *Textile samples* | | | | | | |
| Fabric thickness (mm) | 0.84 | 1.65 | 1.04 | 1.04 | 0.81 | 0.58 |
| +BDU on top | 1.33 | 2.06 | 1.40 | 1.43 | 1.30 | |
| Thermal resistance[a] | 0.156 | 0.193 | 0.139 | 0.148 | 0.147 | 0.121 |
| +with BDU on top ($m^2 \cdot K \cdot W^{-1}$) | 0.165 | 0.208 | 1.166 | 0.160 | 0.164 | |
| Water vapour resistance[b] | 15.0 | 19.5 | 17.1 | 15.4 | 16.0 | 12.5 |
| +with BDU on top ($m^2 \cdot K \cdot W^{-1}$) | 21.7 | 23.8 | 20.2 | 23.8 | 23.4 | |
| Thermal manikin | | | | | | |
| Total thermal resistance[c] ($m^2 \cdot K \cdot W^{-1}$) | | | | | | |
| Underwear ensemble only | 0.136 | 0.164 | 0.140 | 0.144 | 0.144 | |
| Clothing system | 0.243 | 0.268 | 0.256 | 0.248 | 0.250 | |

[a] Includes thermal resistance of air (0.106 $m^2 \cdot K \cdot W^{-1}$);
[b] includes water vapour resistance of air (8.8 $m^2 \cdot Pa \cdot W^{-1}$);
[c] includes thermal resistance of air (0.104 $m^2 \cdot K \cdot W^{-1}$)
BDU = battle dress

*Subjects.* Eight healthy males volunteered for the experiments. Before any testing, the subjects were informed about the purpose of the study, any known risks and their right to terminate participation without penalty. They expressed understanding by signing a statement giving their free and informed voluntary consent. The investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on the Use of Volunteers in Research. None of the subjects did more than two test sessions per week. They had an average age of 23 years, SD 4.9, mass of 74 kg, SD 11.6, height of 177 cm, SD 4.7, DuBois surface area ($A_D$) of 1.91 $m^2$, SD 0.146, maximal oxygen consumption ($\dot{V}_{O_2max}$) of 3.34 l $O_2 \cdot min^{-1}$, SD 0.644, and percentage body fat of 16%, SD 5.2%.

Determination of body density was obtained from hydrostatic weighing (Goldman and Buskirk 1961), and percentage body fat was estimated from density (Siri 1956). The $A_D$ was determined by use of the DuBois equation (DuBois and DuBois 1916). The $\dot{V}_{O_2max}$ was determined for each subject during separate tests using a continuous progressive workload protocol on a cycle ergometer (Rowell 1974).

*Experimental protocol.* Conditions were designed to mimic real-life situations in which sweating and after-exercise chill would develop, and where this type of clothing would normally be worn. Testing occurred in a climatic chamber at an ambient air temperature ($T_a$ = globe temperature) of 5.0° C, SD 0.52°, a dew point temperature ($T_{dp}$) of −3.5° C, SD 0.31° (~54% relative humidity), and an air velocity of 0.32 $m \cdot s^{-1}$. The air flow was created by large fans and directed towards the front of the subject.

To standardize the initial heat content of the five clothing systems and thus eliminate this as a variable for heat exchange between body, clothing and environment during the experiment, a rigid procedure was followed. The clothing was stored in the antechamber at a $T_a$ of 29° C and 20% relative humidity (6.0 kPa) at least 2 h before the experiment began. The elaborate, standardized dressing procedure of the subjects also took place in this antechamber. Each subject reported to the laboratory at the same time of day for all experiments to avoid any circadian variation in body temperature ($T_{body}$). After arrival he was weighed in the nude and then instrumented with chest electrodes for heart rate (HR) and thermocouples for oesophageal temperature ($T_{es}$) and $T_{sk}$. Each piece of clothing, including the shoes, was weighed and then put on the subject. When he was completely instrumented, a dressed body mass was recorded. Upon entering the test environment the subject was instrumented with dew point sensors on the skin underneath the garment before he mounted a cycle ergometer placed on a Potter balance (Potter, West Hartford, Conn., USA). Zero was adjusted on the balance and a calibration was then performed. Approximately 10 min after entering the test chamber the subject began the 2-h test. The test comprised a twice-repeated bout of 40-min cycle exercise (60 rpm; 1.8 kp, SD 0.37) followed by 20 min of rest on the ergometer (EX1, RE1, EX2 and RE2). Each subject always exercised at the same exercise intensity that had been chosen so that it would approximate to 55% of his $\dot{V}_{O_2max}$. The $T_{es}$, $T_{sk}$ and $T_a$, as well as $T_{dp}$ at the skin and in the ambient air were monitored every minute during the test. Changes in body mass were sampled every 20 s and HR was recorded every 10 min. The oxygen uptake ($\dot{V}_{O_2}$) and carbondioxide output ($\dot{V}_{CO_2}$) were measured during the last 5 min of EX1 and RE1, respectively. Two minutes after cessation of the test the subject left the test chamber and undressed immediately in the antechamber. Nude body mass and masses of the individual clothing components were recorded after the subject had undressed.

*Physiological variables.* Electrocardiograms were obtained with chest electrodes and an electrocardiograph (HP 1500 B) (Hewlett Packard, Palo Alto, Calif., USA). The $\dot{V}_{O_2}$ (l $O_2 \cdot min^{-1}$, standard temperature and pressure, dry), $\dot{V}_{CO_2}$ and pulmonary ventilation were measured by open-circuit spirometry using an automated system (Horizon MMC) (Sensormedics Corporation, Anaheim, Calif., USA). The $T_{es}$ was measured by a thermocouple-tipped catheter inserted through the nose into the oesophagus to the level of the heart. The $T_{sk}$ were monitored with a nine-point thermocouple skin harness (calf, thigh, chest, lower back, upper back, upper arm, forearm, hand, and forehead). The thermocouples were constructed in such a way that they could make skin contact without being covered by tape.

The $T_{dp}$ from the back, chest and thigh were obtained by use of automatic dew point sensors (Graichen et al. 1982) directly attached on the skin underneath the garment. Onset of sweating was evaluated from the dew point sensor recordings. Sweat accumulation in the clothing was determined by repeated weighing of each individual clothing component, including the shoes, on a Sauter balance (model K12) (Sauter, Ebin, FRG). Changes in the dressed subjects' evaporation rate during the test were obtained with a Potter platform balance (model 23 B). Total evaporative loss of mass from the subject was determined from the Potter balance recordings, and in addition by weighing the dressed subject on a Sauter balance (model KR120) (Sauter, Ebin, FRG) before and after the experiment.

*Calculations.* Metabolic energy production ($M$) was calculated from the measurements of $\dot{V}_{O_2}$ using the equation of Gagge and Nishi (1977):

$$M = (0.23\,\mathrm{RQ} + 0.77) \cdot \dot{V}_{O_2} \cdot k \cdot 60 \cdot A_D^{-1} \quad (\mathrm{W \cdot m^{-2}}) \tag{1}$$

in which RQ is the respiratory exchange ratio, $\dot{V}_{O_2}$ is the oxygen consumption in l $O_2 \cdot min^{-1}$ and $k$ is the energy equivalent of oxygen (5.873 W·h·l $O_2 \cdot min^{-1}$).

The $\bar{T}_{sk}$ was calculated as an area-weighted average of measurements from the nine different skin sites using the equation [modified from Gagge and Nishi (1977)]:

$$\begin{aligned} \bar{T}_{sk} = {} & 0.05\,T_{hand} + 0.07\,(T_{forearm} + T_{upper\,arm} + T_{head}) \\ & + 0.20\,T_{calf} + 0.19\,T_{thigh} + 0.175\,T_{chest} \\ & + 0.088\,T_{upper\,back} + 0.088\,T_{lower\,back}\ (^{\circ}\mathrm{C}) \end{aligned} \tag{2}$$

Mean body temperature ($\bar{T}_{body}$) was calculated according to Hardy and DuBois (1938)

$$\bar{T}_{body} = 0.8\,T_{es} + 0.2\,\bar{T}_{sk}\ (^{\circ}\mathrm{C}) \tag{3}$$

Sweat evaporated from the dressed subject ($Sw_e$) during the experimental period was determined from the continuous monitoring of loss of mass on the Potter balance corrected for mass of respiratory water loss

$$\frac{0.0173 \cdot M \cdot (5.87 - P_a) \cdot A_D \cdot 60}{2408}\ \mathrm{g \cdot min^{-1}} \tag{4}$$

and metabolic loss of mass

$$\frac{\dot{V}_{O_2} \cdot (44 \cdot \mathrm{RQ} - 32)}{22.4}\ \mathrm{g \cdot min^{-1}}, \tag{5}$$

where $P_a$ is the ambient water vapour pressure. This rate loss of mass converts to the evaporative heat loss rate ($\dot{E}$) in

$\mathrm{W \cdot m^{-2}}$ by multiplying by the factor $\frac{2408}{60 \cdot A_D}$, where the latent heat of water is 2408 $\mathrm{J \cdot g^{-1}}$. Dripping rarely took place, because excess sweat was absorbed in the clothing. The mass of non-evaporated sweat ($Sw_{ne}$) was measured as the difference between clothing mass before and after the experiment, corrected for mass of water absorbed in the clothing from the environment. Hanging the preconditioned clothing system in the experimental environment for 130 min resulted in a mass gain of 18 g. Total sweat production over the test period ($Sw_{tot}$) was calculated as the sum of $Sw_e$ and $Sw_{ne}$.

Vapour pressures at the skin surface and in the ambient air were determined from the local $T_{dp}$ recordings using the Antoine equation. Local $w$ on back, chest and thigh was calculated as

$$w = \frac{P_{sk} - P_a}{P_{ssk} - P_a}, \tag{6}$$

where $P_{sk}$ is the vapour pressure at the skin surface obtained from the humidity sensors and $P_{ssk}$ is the saturated vapour pressure at the local $T_{sk}$ (Berglund et al. 1983). An average $w$ for thigh and torso area was estimated using the actual fraction of the local skin surface area of the total body surface area:

$$w = \frac{0.175\, w_{chest} + 0.175\, w_{back} + 0.190\, w_{leg}}{0.54} \tag{7}$$

*Statistical analysis.* Repeated-measures analysis of variance (ANOVA) was used to determine whether the factor 'knit structure' had any significant effect on thermoregulatory responses during the course of the test or on sweat accumulation in the clothing. An ANOVA was calculated on the data of $T_{es}$, local $T_{sk}$ and $\bar{T}_{sk}$, local and average $w$ and skin evaporation for every 10 min $\left(\left(\frac{8\text{ min} + 9\text{ min} + 10\text{ min}}{3}\right)\right.$ and so on). In the event that an ANOVA revealed a significant main effect, Tukey's critical difference was calculated and used to locate significant differences between means. A paired $t$-test was used to test if there was any difference in thermoregulatory responses between the first and second test periods. Data are presented as mean and SD. All differences reported are significant at the $P<0.05$ level.

## Results

### *Physiological observations*

In the ANOVA the subject factor had a significant influence on all physiological variables.

### *Exercise intensity*

Exercise intensity (W) averaged 56 $\mathrm{W \cdot m^{-2}}$, SD 9.01, during the 40-min cycle periods, and 0 W during the 20 min rest periods.

### *The metabolic energy production*

The $M$ measured during exercise averaged 315 $\mathrm{W \cdot m^{-2}}$, SD 45.5, and during rest 62 $\mathrm{W \cdot m^{-2}}$, SD 11.9. The $M$ was not influenced by the clothing system worn. The exercise intensity corresponded to 52%, SD 4.9% of the subjects' $\dot{V}_{O_{2\,max}}$.

### *Core temperature*

Core temperature as represented by $T_{es}$ (Fig. 1) was not influenced by the knit structure of the underwear worn, except at 50 min where $T_{es}$(K5) was higher than $T_{es}$(K1). In the 1st min of EX1, $T_{es}$ averaged 36.7° C, SD 0.24° for all 40 tests. After 10-20 min of exercise a steady-state value of 37.5° C, SD 0.20° was reached. During RE1 $T_{es}$ decreased quickly to reach an average value of 36.9° C, SD 0.17° just before the start of EX2. The course of $T_{es}$ during EX2 and RE2 was similar to its course during EX1 and RE1, and similar temperature values were measured at the end of the two periods.

### *Mean skin temperatures*

Average values for $\bar{T}_{sk}$ and local $T_{sk}$ for each clothing system are plotted in Fig. 1. Except for the very first minutes of the test, the knit structure of the underwear always significantly influenced $\bar{T}_{sk}$. At the beginning of EX1 $\bar{T}_{sk}$ averaged 31.3° C, SD 0.75° ($n=40$). During the first 10-20 min all $\bar{T}_{sk}$ decreased, although this took place at different rates dependent on the knit structure of the underwear worn. After 10 min of EX1, $\bar{T}_{sk}$(K3) was significantly lower than $\bar{T}_{sk}$(K2) and this difference persisted throughout the rest of the 2-h test. While $\bar{T}_{sk}$(K3) during EX1 continued to decrease to reach a steady-state value of 30.1° C, SD 0.76°, $\bar{T}_{sk}$(K2) began to increase after 17 min of exercise, and reached a steady-state level of 31.5° C, SD 0.80° after 23 min of exercise. The courses of $\bar{T}_{sk}$(K1), $\bar{T}_{sk}$(K4) and $\bar{T}_{sk}$(K5) were alike and they all reached values in between $\bar{T}_{sk}$(K2) and $\bar{T}_{sk}$(K3) (Fig. 1). At 30 min both $\bar{T}_{sk}$(K2) and $\bar{T}_{sk}$(K3) had become significantly different from these three. Immediately after the cessation of EX1 $\bar{T}_{sk}$ increased by 0.1° to 0.2° C with all clothing systems, but after 5 min of rest $\bar{T}_{sk}$ began to decrease again. Throughout RE1 $\bar{T}_{sk}$(K2) was higher than the $\bar{T}_{sk}$ with the other four knit constructions, except in the final minutes of RE1 where $\bar{T}_{sk}$(K2) (30.1° C, SD 1.09°)

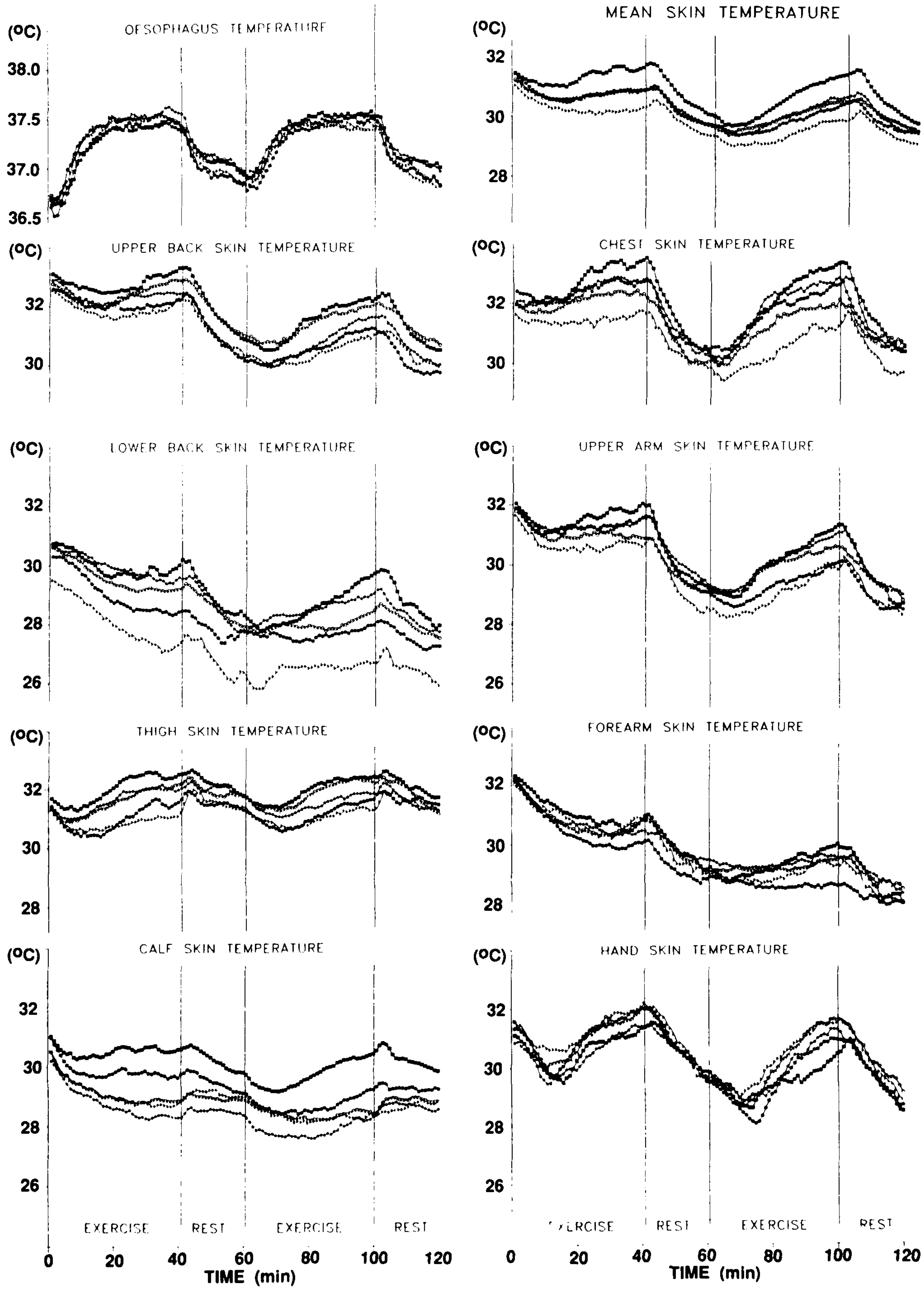


**Fig. 1.** Oesophageal, mean skin temperature and local skin temperatures during the course of intermittent exercise ($n = 8$). ● 1-by-1 rib, ■ fleece, ▶ fishnet, ○ interlock, * double-layer rib

only was significantly higher than $\bar{T}_{sk}$(K3) (29.4°C, SD 0.88°). Due to the decrease of $\bar{T}_{sk}$ during RE1, all $\bar{T}_{sk}$ were lower at the beginning of EX2 when compared to the start of EX1. In all clothing systems the decrease of $\bar{T}_{sk}$ continued over the first minutes of EX2, but after a varying length of time, $\bar{T}_{sk}$ began to increase with all clothing systems: with K2 after 10 min of exercise, with K1, K4 and K5 after approximately 15 min of exercise and with K3 after 20 min of exercise. After 10 min of EX2 (70 min) $\bar{T}_{sk}$(K2) was still higher than $\bar{T}_{sk}$(K3). At 80 min and during the rest of EX2, $\bar{T}_{sk}$(K2) was higher than $\bar{T}_{sk}$(K1), $\bar{T}_{sk}$(K4) and $\bar{T}_{sk}$(K5), which were all higher than $\bar{T}_{sk}$(K3). A comparison of $\bar{T}_{sk}$ during EX1 and RE1 and during EX2 and RE2 showed that at the end of EX2 $\bar{T}_{sk}$ was on average ($n=40$) 0.4°C lower than at the end of EX1, and except for K5 this was significant for each clothing system. The courses of all $\bar{T}_{sk}$ during RE2 were similar to that during RE1, except that all temperatures were from 0.3° to 0.4°C lower during the second period.

*Local skin temperatures*

The course of the various local $T_{sk}$ during the test varied according to location on the body (Fig. 1). They all decreased initially during EX1, but except for the temperature at the lower back and the forearm they either began to increase after a certain time or reached a steady-state level. After cessation of exercise all local $T_{sk}$ had an initial increase before they all decreased throughout the rest periods. At the beginning of EX2, thigh $T_{sk}$ was the only $T_{sk}$ that was not significantly lower than that at the start of EX1. During EX2 all $T_{sk}$, except the forearm, increased much more than during EX1, but only $T_{sk}$ on thigh, chest and forehead reached the same values as at the end of EX1.

The knit structure of the underwear significantly influenced the course of $T_{sk}$ on the trunk (chest, upper and lower back) and on the calf. Differences seemed to exist also in thigh $T_{sk}$; however, these differences were never significant ($0.1 > P > 0.05$). On the calf $T_{sk}$(K2) was always higher than $T_{sk}$(K5), at most times higher than $T_{sk}$(K3) and at some times higher than $T_{sk}$(K4). On the trunk $T_{sk}$(K3) was generally lower than the $T_{sk}$ under the other knit structures. On the chest significant differences only occurred in the last part of the two exercise periods [29 min and 39 min: $T_{sk}$(K2) > $T_{sk}$(K3)] [79 min, 89 min and 99 min: $T_{sk}$(K2) > $T_{sk}$(K3); $T_{sk}$(K5) > $T_{sk}$(K3)]. On the chest no differences in $T_{sk}$ between knit structures were demonstrated during the rest periods. On the lower back $T_{sk}$(K3) decreased more than $T_{sk}$ under the other knit constructions and at 39 min $T_{sk}$(K3) was lower than $T_{sk}$(K2) ($P<0.05$). Also, for the lower back $T_{sk}$(K3) tended to be lower than $T_{sk}$(K4) and $T_{sk}$(K5), but this was only significant occasionally. The $T_{sk}$ on the lower back decreased to quite low values even during work. In most subjects values between 25° and 27°C were recorded, and in the heaviest subject with 23% body fat an even lower $T_{sk}$ of 22°C was measured.

*Mean body temperature*

The $\bar{T}_{body}$ was significantly influenced by knit structure from 29 min and throughout the test (29-119 min: K2 > K3; 69-109 min: K2 > K1; 89-99 min: K2 > K4). The $\bar{T}_{body}$ was on average 0.07°-0.20°C lower in EX2 and RE2 compared to EX1 and RE1 ($n=40$; $P<0.05$); however, this was not significant for K2 at any time, and for K1 and K5 only at 9 min vs 69 min.

*Sweating*

Sweating was considered to begin when the dew point sensors at the skin recorded an increase in vapour pressure. It began at an average of 9 min, SD 3.6 (range 4-19 min) after the start of the exercise. An ANOVA did not confirm any difference in the time to onset of sweating between the live clothing systems; however, there was a tendency towards an earlier onset of sweating in K2 and K5 compared to K1, K3 and K4. There was no difference in the time to onset of sweating between EX1 and EX2. Evaporation of sweat registered on the Potter balance, began at an average of 12 min after the start of the exercise and thus 3 min after the onset of sweating (Fig. 2). No differences between knit types could be demonstrated and no differences between EX1 and EX2. The $\dot{E}$ was on average 50, 40, 45 and 43 $W \cdot m^{-2}$ in the periods EX1, RE1, EX2 and RE2 respectively (that is, 2.4, 2.0, 2.2 and 2.1 $g \cdot min^{-1}$ respectively) ($n=40$). No significant differences could be attributed to the knit constructions, as the variation in $\dot{E}$ was rather large. However, in EX1 $\dot{E}$(K3) and $\dot{E}$(K4) tended to be lower than $\dot{E}$ with the other knit structures ($0.1 > P > 0.05$). The $Sw_e$ was significantly influenced by knit construction and the differences

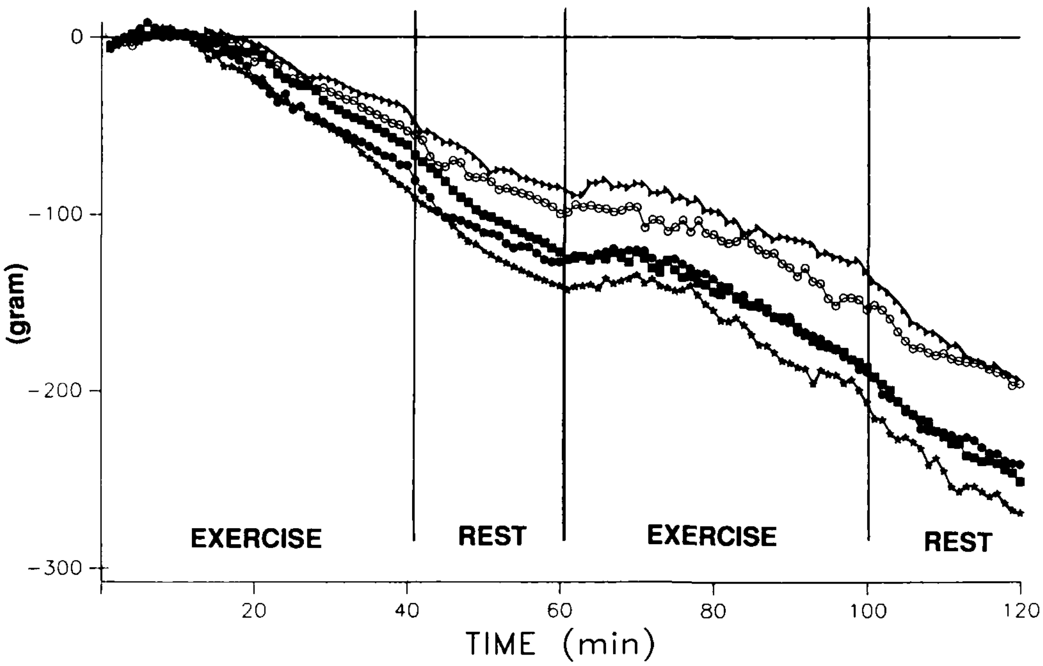


**Fig. 2.** Average evaporative loss of mass during the course of intermittent exercise ($n = 8$). Symbols as in Fig. 1

between the clothing systems increased with time (Fig. 2). At the end of EX1 (40 min) $Sw_e$(K3) was lower than $Sw_e$(K5); at the end of RE1 (60 min) and EX2 (100 min) $Sw_e$(K3) was lower than $Sw_e$(K1), $Sw_e$(K2) and $Sw_e$(K5), and $Sw_e$(K4) was lower than $Sw_e$(K5). At the end of the test (120 min) both $Sw_e$(K3) and $Sw_e$(K4) were lower than $Sw_e$(K1), $Sw_e$(K2) and $Sw_e$(K5) (Fig. 3). The total $Sw_{ne}$ moisture absorbed in the clothing ensemble during the experimental period was also significantly influenced by the knit structure of the underwear (Fig. 3). More sweat was found in the clothing when K2 was worn compared to K1, K3 and K4. Of this, non-evaporated sweat, only 8%, 22%, 8%, 10% and 11% were located in the underwear of the five clothing systems (K1 to K5 respectively). The $Sw_{tot}$ could only be determined at 120 min, when $Sw_{tot}$(K3) and $Sw_{tot}$(K4) were lower compared to both $Sw_{tot}$(K2) and $Sw_{tot}$(K5) (Fig. 3).

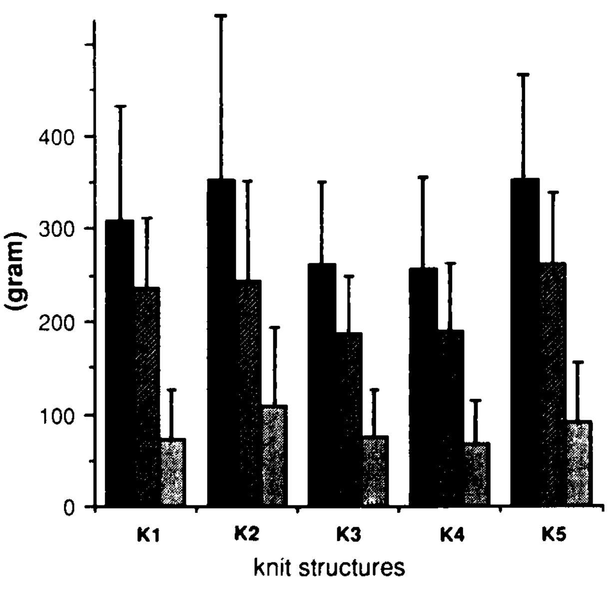


**Fig. 3.** Total sweat production, evaporated and non-evaporated sweat (mean and SD). 1-by-1 rib (K1), fleece (K2), fishnet (K3), interlock (K4), double layer rib (K5). ■ Total sweat; ■ evaporated; □ unevaporated

*Skin wettedness*

The knit structure of underwear significantly influenced the degree of $w$ during the course of the intermittent exercise (Fig. 4). After onset of sweating, $w$ increased abruptly in both exercise periods to reach a steady-state or near steady-state level. Immediately upon the cessation of exercise, the percentage $w$ on the thigh increased, a tendency that was also seen on the chest, whereas on the upper back no such increase was observed. After 3-4 min of RE1, $w$ began to decrease and this decrease continued even after EX2 had begun. With the different knit structures average $w$ reached values from 50% to 68% at the end of the exercise periods. The $w$(K2) was always higher than

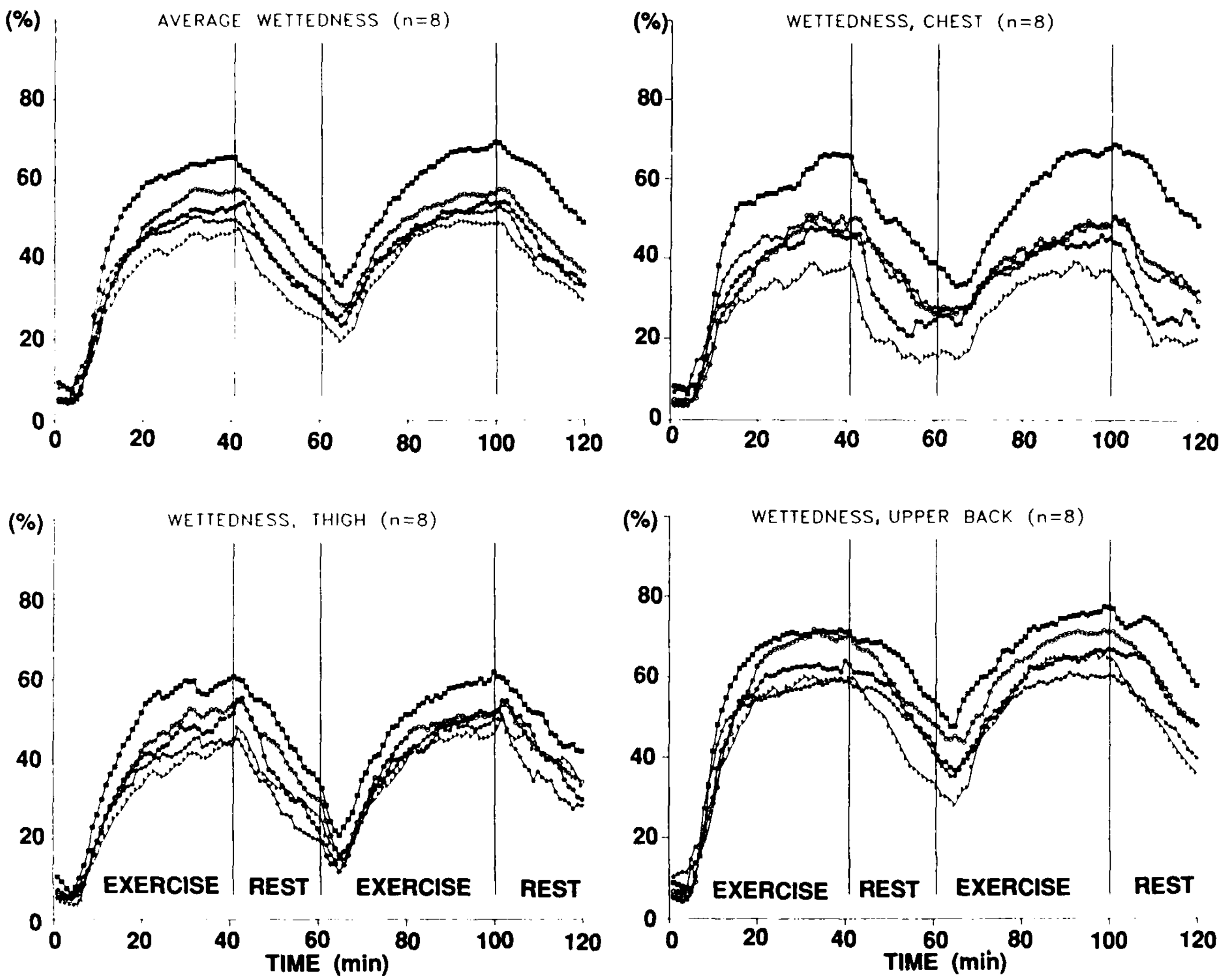


Fig. 4. Average skin wettedness, and locally on upper back, chest and thigh during the course of intermittent exercise ($n=8$). Symbols as in Fig. 1

$w$(K3). From 30 min to the end of RE1 $w$(K2) was higher than $w$(K1), $w$(K3) and $w$(K5), and from 90 min to the end of the test $w$(K2) was higher than the average $w$ compared with all the other knit structures. Throughout the test $w$(K3) tended to be lower than $w$ under all the other knit structures, but being only significant at 30 min. On the upper back $w$ was generally higher than at the chest and the thigh, reaching average values from 59% to 71% at the end of EX1 and from 60% to 77% at the end of EX2. Influence of knit structure on upper back $w$ was significant at 60 min and 70 min (K2 > K3), and at 110 min and 120 min (K2 > K3; K2 > K5). At the chest the influence of knit structure on $w$ was more pronounced. Except for the first minutes of the two exercise periods (10 min and 70 min) $w$(K2) was always higher than $w$(K3); $w$(K2) was mostly (20–40 min and 90–120 min) higher than $w$(K1), and at 40 min and 90–110 min higher than $w$(K4) and $w$(K5). At the thigh $w$(K2) was higher than $w$(K3) and $w$(K5) at 30–50 min and at 100–110 min. Generally, $w$ was slightly higher in EX2 and RE2 compared to EX1 and RE1.

## Discussion

Knit structure of the underwear in a prototype two-layer clothing ensemble had no influence on core temperature, but had a significant influence on the thermoregulatory responses at the skin during intermittent exercise in a cold environment. Both the degree and the effectiveness of sweating during the periods of work-produced heat stress and the cooling of the skin during the

subsequent rest periods varied depending on the knit structure of the polypropylene underwear worn. Earlier studies on the physiological significance of underwear during intermittent exercise in the cold have focused on the importance of material fibre type (Vokac et al. 1976; Holmér 1985). Only small differences were observed. Thus, the knit structure of underwear is of far more importance regarding thermoregulatory responses than fibre type, when working in the cold.

The underwear constructions selected for this study varied in thickness (three levels) and in porosity (three levels), and these differences were reflected in the measured thermal characteristics of the underwear textiles (Table 1). When doing a comparison of the thermal characteristics of the five clothing systems under stationary conditions as described for standard measurements on two-layer textile samples and on a thermal manikin, the differences in thermal resistance and moisture vapour transport were small. This was expected for the measurements on the non-moving manikin, where the tight-fitting underwear adds little extra insulation to the clothing ensemble. The insulation of the clothing ensemble is primarily determined by the amount of enclosed non-moving air, and thus by the design and fit of the outermost garment (McCullough et al. 1983). Some of the differences found in the standard measurements of the textiles were reflected in the thermoregulatory responses. The heavy fleece structure (K2) was the thickest textile, had the highest thermal and water vapour resistance, and it also resulted in the most pronounced heat defense reactions with highest $T_{sk}$, highest $w$, most $Sw_{tot}$, and most $Sw_{ne}$. However, the K1 system with the thin 1-by-1 rib-knit underwear, which had the lowest thermal resistance and a comparably low water vapour resistance, did not result in the lowest heat defence reactions in the human tests. This was found in the K3 system with the open fishnet underwear, where we observed the lowest $T_{sk}$, the lowest $w$ and a low $Sw_{tot}$ that also resulted in a smaller $Sw_e$. This comparably cooler response could not have been expected, based on the textile and manikin data, where the K3 system ranked second with regard to thickness and thermal resistance although lowest in water vapour resistance.

The differences between the results from static measurements on samples of textiles and of garments on a manikin, respectively, and responses in human tests must be explained from the dynamic condition within the microclimate of the clothing systems during the exercise in the actual test environment. An external air velocity of $0.32\ m \cdot s^{-1}$ removes part of the insulating boundary air layer adjacent to the clothing system and thus lowers the resistance to both diffusion of heat and water vapour (Burton and Edholm 1955). The external air may also penetrate into the clothing, producing convection within the entrapped air, reach the underwear and then, eventually, reach the air directly at the skin surface. These convective air movements will add to those created within the microclimate by bodily movements, resulting in the bellows or pumping effect (Vokac et al. 1973). An open structure such as the fishnet construction will allow for the moving air to sweep directly over the skin, whereas a heavy and tight construction such as K2 will only allow a limited amount of air to reach the skin surface. Although $T_{sk}$ will be lower with K3, a steeper gradient from the skin surface to the microclimate will therefore result with regard to temperature and water vapour pressure compared with the other constructions, especially K2. The $T_{sk}$ and $w$ reflect this, reaching lower values under the K3. Even without the external air velocity, the pumping of air within the clothing ensemble would probably have resulted in differences in the thermoregulatory responses at the skin in this study. In a clothing ensemble with more layers than applied here, the external air may not reach the skin under tight-fitting underwear, depending on closures and the air permeability of the outer layers.

Air movement within the clothing microclimate can explain the differences found in $T_{sk}$, but not the differences observed in the sweat data. With $\bar{T}_{sk}$ as one determinant of sweat production, the observed high sweat production with K2 and the low production with K3 may result from different $\bar{T}_{sk}$. However, with K1, K4 and K5, $\bar{T}_{sk}$ were not different, but sweat production tended to start earlier and was significantly higher with K5 than K4. The minor differences in the textile characteristics do not provide an explanation for this. Of the total sweat produced, 74% was evaporated, 26% unevaporated and the ratio non-evaporated:evaporated was 0.36 in both K4 and K5; but the $Sw_{tot}$ was significantly larger with K5 than K4. It was interesting to note in all clothing systems that it took approximately 3 min from the start of sweat production until sweat began to evaporate to the environment.

Differences in the thermoregulatory responses among regions of the body were quite large. Generally, the back seemed warmer than the front. Differences between chest and upper back in regard to $T_{sk}$ and $w$ were small with K2; however,

with the other knit structures, and especially with K3 differences became more pronounced. This supports the theory proposed above that air blowing towards the front of the subject increases the convective heat exchange and removes humidity-laden air, thus ameliorating the conditions for diffusion of vapour and heat energy. The back is the lee side and, therefore, is less influenced by the air velocity. This would also be expected to occur at the lower back; however, here unusually low temperatures were recorded. Whether this implies an effective ventilation of the clothing microclimate in this area, a thicker subcutaneous fat layer than at the other measuring sites on the trunk, or sweat running down the back or moving down in the clothing at the back to stop at the lower back so that a more effective evaporative cooling takes place at the skin, is unknown, and could be studied further. The greatest effective of convective cooling and the pumping effect was observed on the legs, where cessation of exercise caused an immediate increase in both $T_{sk}$ and $w$ before both slowly began to decrease again. Although the BDU trousers were closed at the ankles, there was a large variation in $T_{sk}$ on the calf dependent on the knit structure of the underwear.

It was decided to use an intermittent exercise test rather than a single exercise period followed by a period of rest as used by Holmér (1985). It was hypothesized that a dampening or wetting of the clothing system would occur over the course of EX1 and RE1 and that this might change the course of the thermoregulatory responses in the second period. A lower $\bar{T}_{sk}$ and a higher $w$ was actually observed. The hydrophobic polypropylene fibre material in the underwear hindered extensive sweat accumulation in the underwear (maximal average was 25 g in K2). Instead, accumulation of sweat took place in the outer garment layer, especially the jacket. Therefore, we did not have a sweat-soaked textile in contact with the skin that increased the conductive heat loss, and, the lower $\bar{T}_{sk}$ recorded in the second period must be explained by a lowering of the total insulation of the clothing system caused by the dampening or wetting of the ensemble. Earlier studies have shown that the wetting of clothing lowers its insulation (Hall and Poltke 1956; Pugh 1966). With the method used in the present study it was not possible to decide when the absorption of sweat took place. However, the first minutes after cessation of exercise, when sweat production was still high but ventilation was considerably decreased, was probably the period of the most sweat absorption.

For work in a cold environment it is usually recommended not to dress too warmly. The rationale is that with a warmer dress more sweat will be produced, more sweat will then be absorbed in the clothing, resulting in a greater decrease in clothing insulation, and finally a greater cooling of the body in subsequent rest periods. The data obtained in the present study do not support this idea. After 20 min of rest, $\bar{T}_{sk}$ was still higher with the warm K2 underwear compared to the K3 underwear. There is no reason to believe that a longer rest period would change this. However, with a more hydrophilic fibre type material such as cotton, this may not be the case.

In summary, knit construction of underwear in a clothing ensemble had no influence on core temperature, but had a significantly large influence on the thermoregulatory responses at the skin during intermittent exercise in a cold environment. Both the degree and the effectiveness of sweating during the periods of work-produced heat strain, and the chilling of the skin during the consecutive rest periods varied dependent on the knit structure of the polypropylene underwear worn.

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